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"Environmental Processes and Spectral Reflectance Characteristics Associated with Soil Erosion in Desert Fringe Regions."

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1.1 Introduction

As a result of revisions in the availability and quantity of TM data to be provided for the purposes of this study, several changes have been made in the work plan and anticipated results of this research program. These changes have been made necessary by the greatly reduced amount of data to be provided by NASA, but in so doing it has been our intent to retain the essential scientific objectives of the original study. The revised research plan and its relevance to and relationship with the original study objectives are described below.

The original thrust of the study was to monitor three field areas over the course of three years, for the purpose of establishing spectral baselines for the reflectance characteristics of these areas. The three areas taken together comprise an environmental series ranging from hyperarid to semi-arid, with desertization processes operational or incipient in each. The long-range objective of this monitoring approach was to arrive at apoint at which normal seasonal variations in reflectance (as seen with TM data and corroborated through field and laboratory study) are well-characterized and predictable, so that aperiodic spectral changes resulting from soil erosion, vegetation damage and associated surface processes would be distinguishable as departures from the norm.

The requirements of such a study are data-intensive. In order to accommodate the drastically reduced availability of TM data for the purposes stated, the following changes have been put in place:

1. Full-scale documentation of spectral baseline characteristics at an intensive temporal scale will be done for two of the three field sites rather than all three. The study areas in Mali and Botswana will be studied for baseline establishment, while the third site (Bahariya in Egypt) will be studied for net dune sand transport in the spatial domain rather than the spectral. To further conserve data, the establishment of baselines will be restricted to an eighteen-month period, at slightly broadened time intervals, and will rely on archival MSS data to establish longer-term trends. In fact, such MSS data have already been acquired by the PI, as part of a precursor study of the Tombouctou region. To take advantage of this data in hand, the field site in Mali was "skidded" northeast by one path and one row. The slight shift of this field site does not significantly impact the processes to be studied.

2. Similarly, baseline reflectances will be established for the Okavango study site over an eighteen-month period, with selected

earlier acquisitions to determine long-term trends. This site is important to the study objectives, since it is here that drought pressure has been great while land use and associated damage have been minimal.

3. For the Bahariya site, objectives have been revised, and will concentrate on the spatial distribution of sand as a function of dune migration, and the environmental response of such dune migration into oases and agricultural areas. Aerial photographs taken in the 1940's have been obtained to supplement TM data, along with MSS data acquired in 1976 and 1984. These data will provide information on long-term trends in dune migration as well as responses to dune movement.

These revisions retain the essence of the study, which is a quantitative approach to documenting seasonal color and brightness changes in the semi-arid environment. The resulting series of baseline curves will be detailed enough in both the spatial and spectral domains to be of use in short-term, aperiodic change detection, for the specific sites under study and potentially for areas that are environmentally and geologically similar. Because of the reduced frequency of data acquisition, other data sources, both orbital and ancillary, will be relied upon to supplement and substantiate the patterns that emerge from the study. The long-term applicability and significance of the work, however, is not compromised.

2.0 <u>Progress</u>

Two TM scenes were acquired over the past six months, permitting accomplishment of some Phase 1 goals. A scene was acquired for the Bahariya, Egypt field area, and one was acquired covering the Okavango Delta site. Several additional scenes or quadrants are on order.

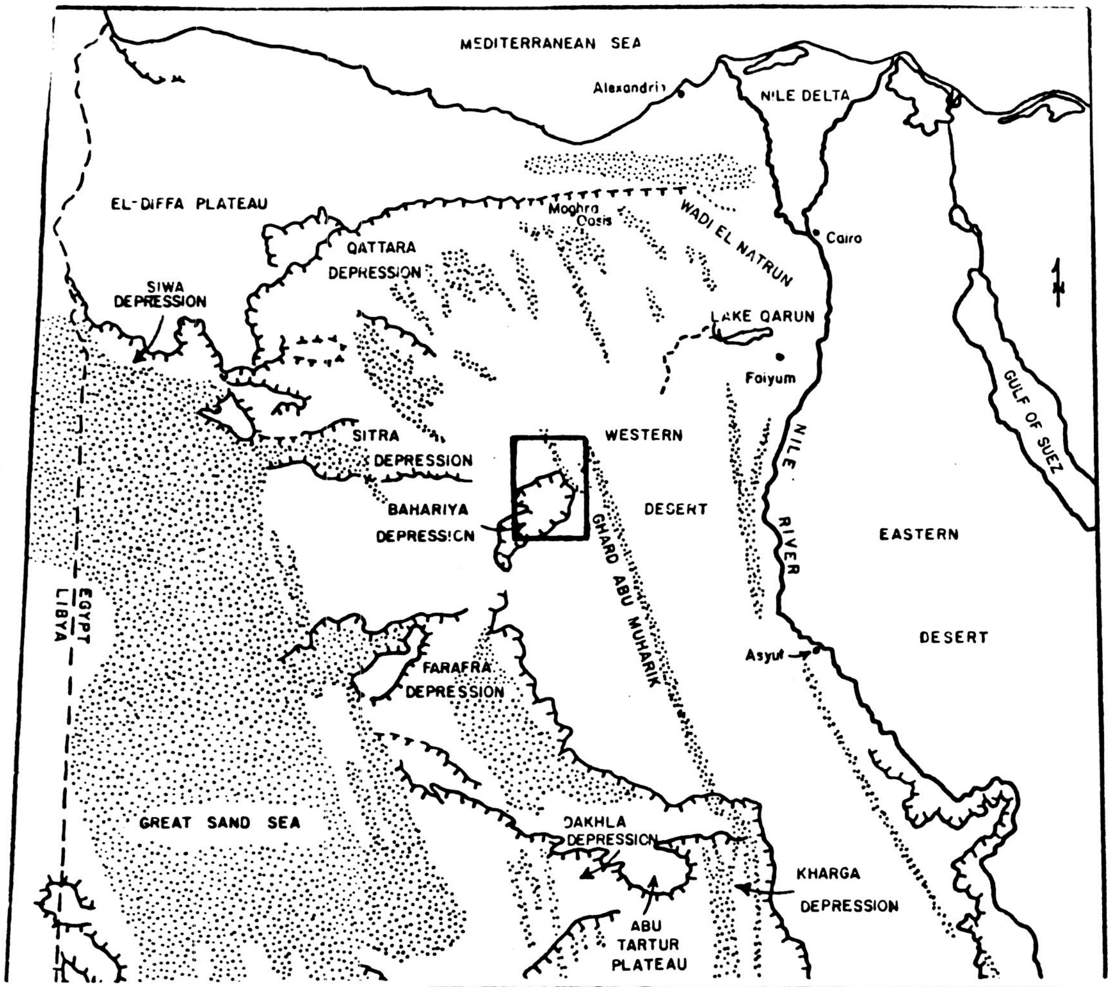
2.1 Bahariya Depression, Egypt

As mentioned in the previous section, aerial photos taken in the 1940's have been added to the study of dune migration in the Bahariya Depression, in order to extend our baseline over forty years' time. Used together with both the TM acquisition and MSS data obtained for a previous study, these complementary datasets indicate substantial natural environmental changes due to dune migration, as well as the impact of human habitation in an active sand transport regime. Additionally, the spectral information obtained from the TM data and from spectra acquired for field samples are proving useful in mapping compositional differences of desert floor sediments and lag surfaces as well as dune sands.

The central prt of the Bahariya depression is covered by irregular sand masses from three to five kilometers wide. The distribution of these sand masses is controlled primarily by the relict fluvial topography of the northern escarpment of the depression, which acts to channel the movement of sand from the plateau above across the escarpment and into the depression. Within the depression, isolated plateaus and hills create local variations in the predominant northerly winds, and exert additional control on the patterns of aeolian erosion and deposition. The boundaries of these sand masses as mapped on air photos and Landsat images have changed little over the forty-year period, although local movement of linear duneforms has occurred. The most evident changes within the depression are due to cultural influences: approximately 40% of the area occupied by active sand deposits in the 1940's is seen to be cultivated in 1985 TM data. Areas of the sand masses that formerly had a high density of individual vegetated mounds and coppices are now joined by belts of cultivated fields (Figure 2.1.1). Field work conducted in late 1985 substantiate the environmental changes observed in the aerial coverage and TM data. Inhabitants of Bahariya are increasingly cultivating the dune sand that occupies the lowest parts of the depression, rather than losing fertile land to dune encroachment. Although such areas have the highest risk of sand infiltration into cultivated fields, the availability of near-surface groundwater makes this activity a natural consequence of coexistennce with active aeolian sand.

The next phase of work in Bahariya will be to utilize the TM spectral information to fully characterize reflectance properties of dune sands and interdune corridors. Samples acquired in the field for this purpose will be analyzed petrographically and using the Hand-Held Ratioing Radiometer for spectral information. These data will be co-registered with TM data, and thematic maps of the spatial distribution of spectrally similar materials will be developed.

Figure 2.1.1: At left is a sketch map showing the location of Bahariya in the Western Desert of Egypt. An enhanced Landsat MSS view of the depression and its northern rim is shown at right; the white box outlines the area in which agricultural development has taken place on top of the dune sand that has been encroaching upon oases within the depression. An enhanced TM subset image of this area is shown at lower left. The agricultural scheme is clearly visible.



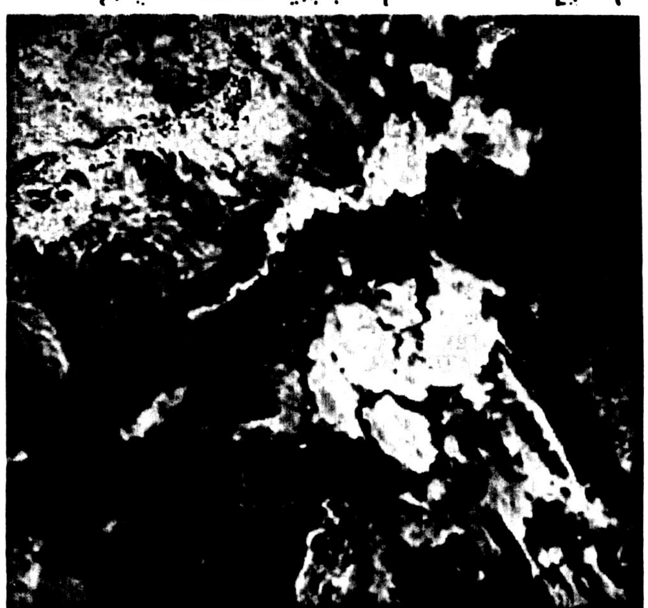


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Fig. 2.1.1

2.2 Okavango Dunes, Botswana

Investigations at the northwest Botswana study site have concentrated upon a system of large linear (alab) dunes possessing an average wavelength of 2 kilometers and an east-west orientation. These dunes exist tothe north and west of the Okavango Swamp, the pseudodeltaic end-sink of theinternal Okavango-Cubango-Cuito drainage network.

Analysis has focused upon a TM scene acquired by Landsat 5 on May 11, 1985. A subset of the TM scene was reformatted for intensive study, and consists of a 2300x2300 pixel array that stretches from the Tsodilo Hills in the northwest corner of the study site eastward to the border of the Okavango River flood plain, and from well-defined linear dunes in the southwest to a sequence of fluvially-modelled dunes in the southeast (figure 2.2.1). Interpretation of TM data for this area began with principal components analysis and geomorphologic mapping of primary landform units based on visual interpretation and the structure of the data matrix as determined from the principal components analysis. Following this intitial processing, an unsupervised maximum likelihood classification was conducted. The statistics for this procedure were generated on a pixel-by-pixel basis through a multichannel hierarchial clustering operationn with equal bias between aeolian and fluvial environments. Twenty-nine classes were generated and winnowed down to nineteen. Further winnowing may eventually be necessary. At the completion of the principal components analysis and the unsupervised classification, a full-resolution image was constructed of the study site.

Visual interpretation and preliminary mapping reveals that the Okavango Delta region of northwestern Botswana accomodates landforms of fluvial, aeolian and lacustrine origin. These landforms have evolved from a climate oscillating between wet and dry periods, thus superimposing landforms of contrasting climates. The present semi-arid, savanna-like climate of Botswana provides for an annual rainfall of less than 200 mm in the desert southwest corner to over 650 mm in the northeast corner of the country. Maun, in south-central Botswana beside the Okavango Delta, receives an annual rainfall of 472 mm. The inland delta responds to inflow from the Angolan highlands with a flood surge in March, but it is not until July or August when flooding peaks in the lower delta, nearly 300 km to the souteast. Thus, local rainfall is out of phase with local flood stages. The goal of the next phase of work in this area is to establish a sequence of TM scenes that document the timing of the flood surges and accompanying inundation and infiltration of the dune environment.

As interpreted by both spectral and photogeologic study of the TM data, the Kalahari Sand, present as dunes and genly undulating plains, dominates the study site. The Kalahari Sand is Late Pliocene to Recent in age and mantles over 90% of the underlying bedrock (Poldervaart, 1955). Four major sand types have been mapped (Baillieul, 1975); the three types in the western two-thirds of Botswana are quartzose aeolian sands and are genetically related to the Karroo Supergroup sandstones and the Ghanzi Group sandstones (both Proterozoic). These aeolian sands are reddish-brown to buff white in color and are usually a few meters in thickness, but may exceed 30 m in places. (The fourth type of sand is fluvial in origin, is restricted to the eastern third of the country, and thus does not occur in the field area). Despite the abundance of sand in the Kalahari, all dunes in areas above the 200 mm isohyet have been stabilized by a cover of grass, shrub, and Acacia scrub, or in the north and west, by Mopane woodland.

Image data show that the dunes of the Okavango Delta area are strikingly linear and parallel. Now degraded and breached, they once stood approximately 90 m high and had lengths of several tens of kilometers. Mappable differences exist in dune and interdune corridor morphology, and spectral variations occur across the dune system. The unsupervised classification delineated eight spectral classes within the dune sands and related units across the dune system within the study area west of the delta. Although both dunes and interdune corridors west of the delta are vegetated and exhibit subdued dune crests, the interdune corridors are well-defined, narrow, linear, and marked by very high-reflectance margins. In comparison, the related dunes north of the delta are bevelled and breached by ephemeral distributaries of the Okavango system. These differences indicate that although modification of the dunes north of the delta is dominated by surface runoff and decantation of silts into the interdune corridors, moisture primarily is made available to the western dunes through infiltration rather than overland flow. The bright margins of the western interdune areas may represent salinized soils. Broad, irregular color and brightness variations are superimposed on the regular pattern of the dunes, representing differences in vegetation, soil characteristics, and/or soil moisture (Figure 2.2.2).

Statistics pertaining to the spectral classes established for the May 1985 TM scene reveal that the differences between classes are primarily related to panchromatic brightness rather than individual bandpasses, with the exception of the two darkest classes (Table 1). This relationship suggests two approaches for additional study: 1) that a linear mixing model may suffice to relate the previously-defined classes; and 2) that calculations of residuals or departures from mean values may yield further spectral information. Verification of the nature of these differences in spectral response will form the core of field work planned for June 1987.

Additional work in progress includes improving and updating our program developed to read and analyze the World Monthly Surface Station Climatology dataset, obtained on CCT to form a database for weather-related variables within the study. Temperature,, precipitation, relative humidity, and other available meteorological parameters for the Botswana weather stations have been analyzed and will be the focus of further statistical analysiis, in order to correlate meteorological data with observed spectral differences.

The next phase of analysis with respect to TM data will concentrate on the definition of transects across and along dunes, to record variations in dune morphology and spectral reflectance. These transects will aid in definition of interdune corridors, dune crests, and vegetation cover, and will provide the parameters required for a mathematical model of duneform within the study area. These transects will then serve as overlays for analysis of subsequent TM acquisitions, to ensure co-location of spectral curves established through time.

(References: Baillieul, T.A., 1975, J.Sed.Pet.45:494-503; Poldervaart, A., 1955, in Proc. 3rd Pan-African Congress in Prehistory, Livingstone, 1955, p.106-114.)

Figure 2.2.1: Sketch map showing the location of the study site in the dune system west of the Okavango Delta of northwestern Botswana; a principal components enhancement of the study site is presented at lower left. The linear Kalahari dunes that cover most of the site are clearly visible.

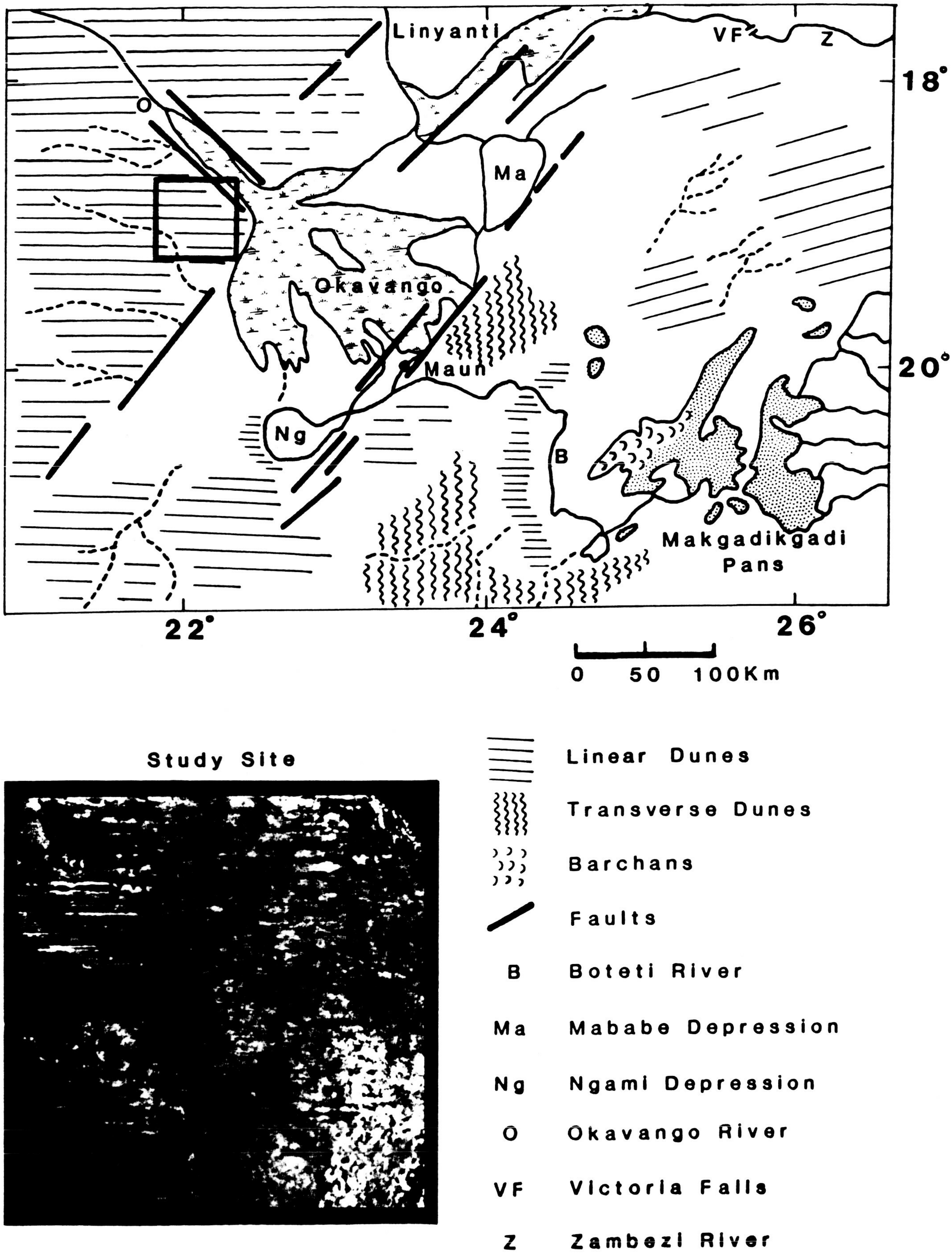
Linyanti
VF
Z
18°
O
Ma
Okavango
Maun
20°
Ng
B
Makgadikgadi
Pans
22°
24°
26°
0 50 100Km
Study Site
Linear Dunes
Transverse Dunes
Barchans
Faults
B Boteti River
Ma Mababe Depression
Ng Ngami Depression
O Okavango River
VF Victoria Falls
Z Zambezi River

Fig. 2.2.1

Figure 2.2.2: Statistics pertaining to the principal components analysis performed for the study area. Shown below these figures are the first principal component image resulting from this analysis, and an image generated based on a maximum likelihood classification procedure applied to the initial field test locale, selected from the study site based on variations observed in the principal components analysis.

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CHANNEL STATISTICS

CHANNEL	1	2	3	4	5	6	7
MEAN	89.00	39.58	52.07	68.26	112.58	153.45	56.29
S.D.	7.42	4.92	8.77	8.05	15.65	2.81	10.60
COV.	0.08	0.12	0.17	0.12	0.14	0.02	0.19

COVARIANCE MATRIX

55.10						
34.49	24.22					
58.80	41.52	76.84				
42.53	31.70	54.87	64.88			
93.86	67.60	126.90	91.78	244.85		
5.68	3.98	8.69	1.22	21.50	7.91	
65.93	46.40	85.85	58.38	158.68	13.84	112.39

PRINCIPAL COMPONENT STATISTICS

TRANSFORMATION MATRIX

CHANNEL	1	2	3	4	5	6	7
1	0.039	0.034	0.093	0.030	0.047	-0.053	0.032
2	0.041	0.035	0.049	0.012	-0.013	0.021	-0.188
3	0.042	0.016	0.031	0.016	-0.065	0.067	0.033
4	0.035	0.097	-0.059	-0.012	0.032	0.012	0.008
5	0.043	-0.023	-0.025	0.023	-0.007	-0.022	-0.002
6	0.019	-0.102	-0.008	0.124	0.234	0.213	-0.002
7	0.043	-0.025	0.011	-0.077	-0.019	0.009	0.002

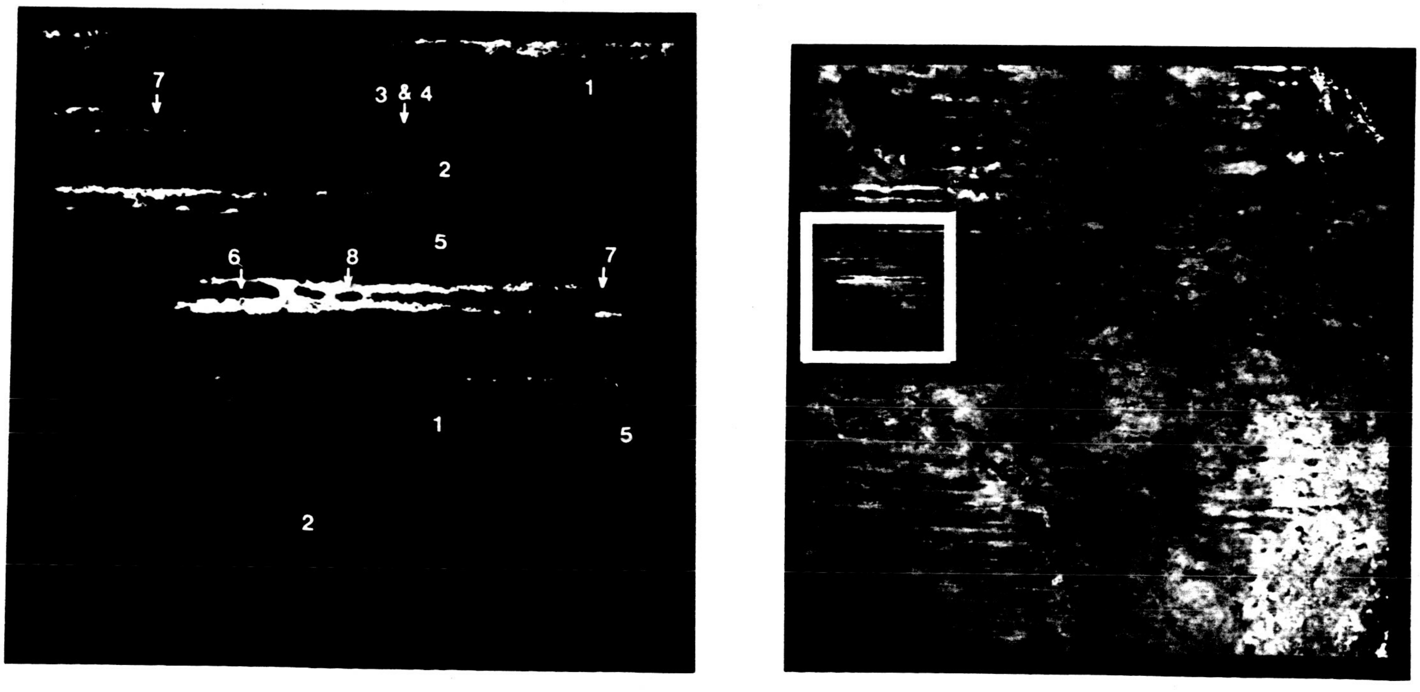
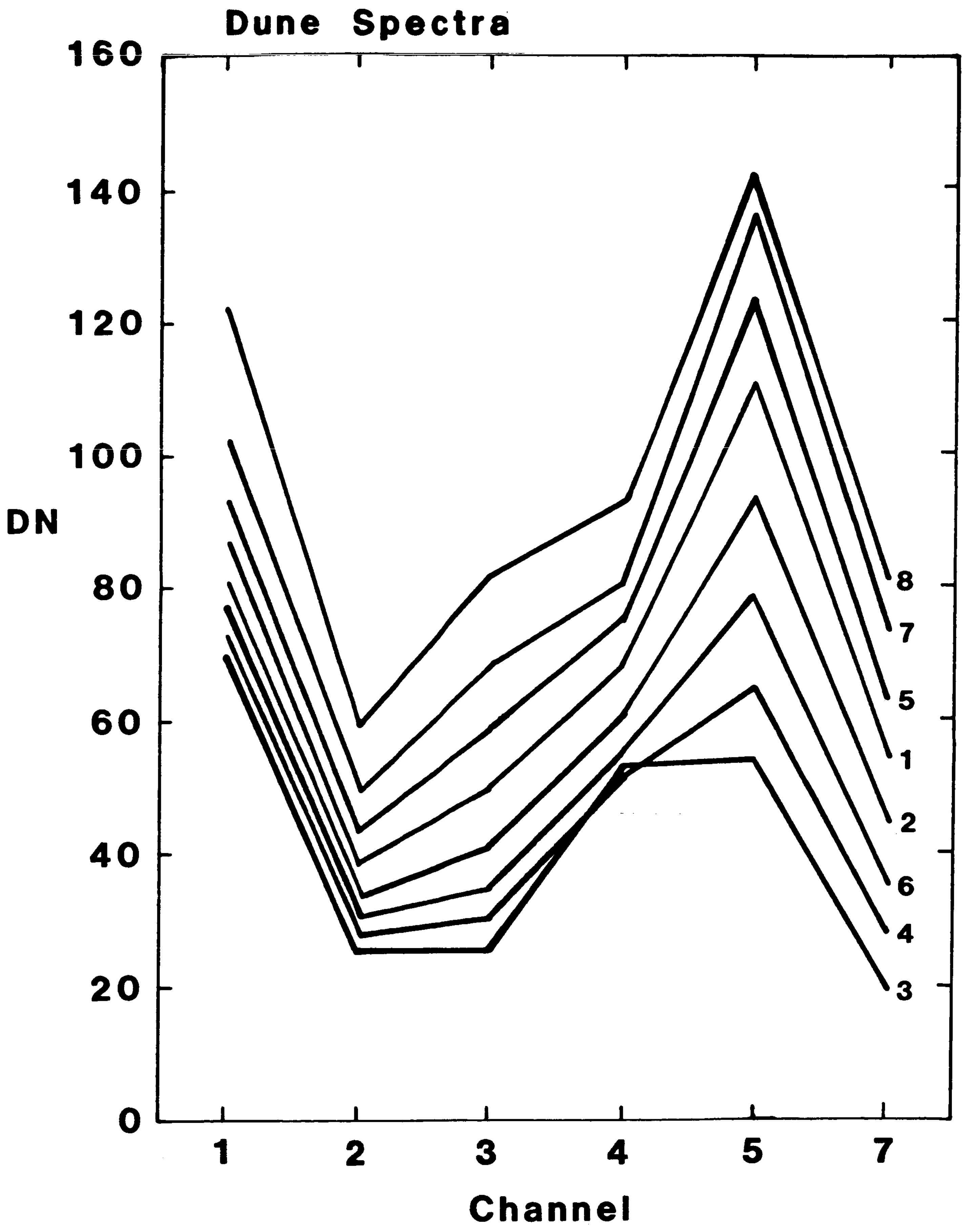


Fig. 2.2.2

Figure 2.2.3: Spectra of the eight dune-related units, sequentially generated through an unsupervised maximum likelihood classification algorithm and shown in the previous figure, are presented. The thermal channel was omitted from the classification procedure. With the exception of Class 3, there is a strong parallelism among spectral curves, which indicates that overall brightening separates these classes rather than strong band-specific information. Thus, a linear mixing model can be used to account for variations within the dune materials. This trend will be examined for consistency with respect to TM data to be acquired later in the study.



Dune Spectra
160
140
120
100
80
60
40
20
0
DN
8
7
5
1
2
6
4
3
1
2
3
4
5
7
Channel

Fig. 2.2.3

2.3 Tombouctou/Azaouad Dunes, Mali

One archival scene and two TM acquisitions are on order, but at present no TM data have been acquired for this study area. However, extensive use has been made of MSS data and field measurements in preparation for TM analyses.

Preliminary geomorphologic mapping of the stabilized linear dunes that occupy the Azaouad Depression and that surround Tombouctou yields a complex sequence for their evolution. The dunes trend roughly N 67 E with nominal wavelengths of 1500 meters (Figure 2.3.1). The construction of the Azaouad dunes has been dated to a hyperarid episode between 20,000 and 12,000 years before present, and stabilization is thought to have occurred during a humid phase between 12,000 and 8,000 years bp. Holocene remobilization of the southern Erg of Azaouad sands between 8,000 and 7,000 ybp, followed again by stabilization between 6,000 and 5,000 ybp, has been suggested based on geomorphologic relationships and the climatic chronologies established for other Sahelian regions (Flohn and Nicholson, 1980; McIntosh, 1983). Intercalated with the Azaouad dunes are relict fluvial channels leading north into the Azaouad Depression. These channels represent either former courses or major distributaries of the Niger River; prior northward drainage of the Niger into the now-hyperarid Sahara has been suggested.

Although most of this relict fluvial system and associated soil units are indistinnguishable in unenhanced MSS data, spatial filtering of the digital MSS data allowed removal of the 1500-meter wavelength dune pattern. Residual images show an extensive network of the Azaouad paleochannels. Although only first- and second-order channels are visible in MSS data processed in this way, we anticipate that application of the same filter to TM data will reveal more detail in the channel systems, as well as better spectral resolution on the soils in which the channels are inscribed. At MSS resolution, the Azaouad paleodrainage is poorly organized, with no apparent control of visible channels by the surrounding sand. No first-order channels are seen to parallel the dune trend or to run within interdune corridors, although there are indications that smaller, higher-order distributaries may do so. The observed morphology indicates that these channels postdate the formation of the Erg of Azaouad dunes. Fluvial modelling and breaching of the dunes point to water volumes sufficient to overcome the extremely low regional gradient and physical barrier of the sand. No channels are observed in the region showing most evidence of Holocene dune remobilization and reworking, indicating that the channel system may predate this episode (8,000 - 7,000 ybp). The morphometry of the channel complex is similar to that of the present Inland Niger Delta in the region of the Erg of Bara, 200 km to the south. This suggests a possible northward extension of the Inland Delta across the southern Azaouad between 10,000 and 8,000 ybp.

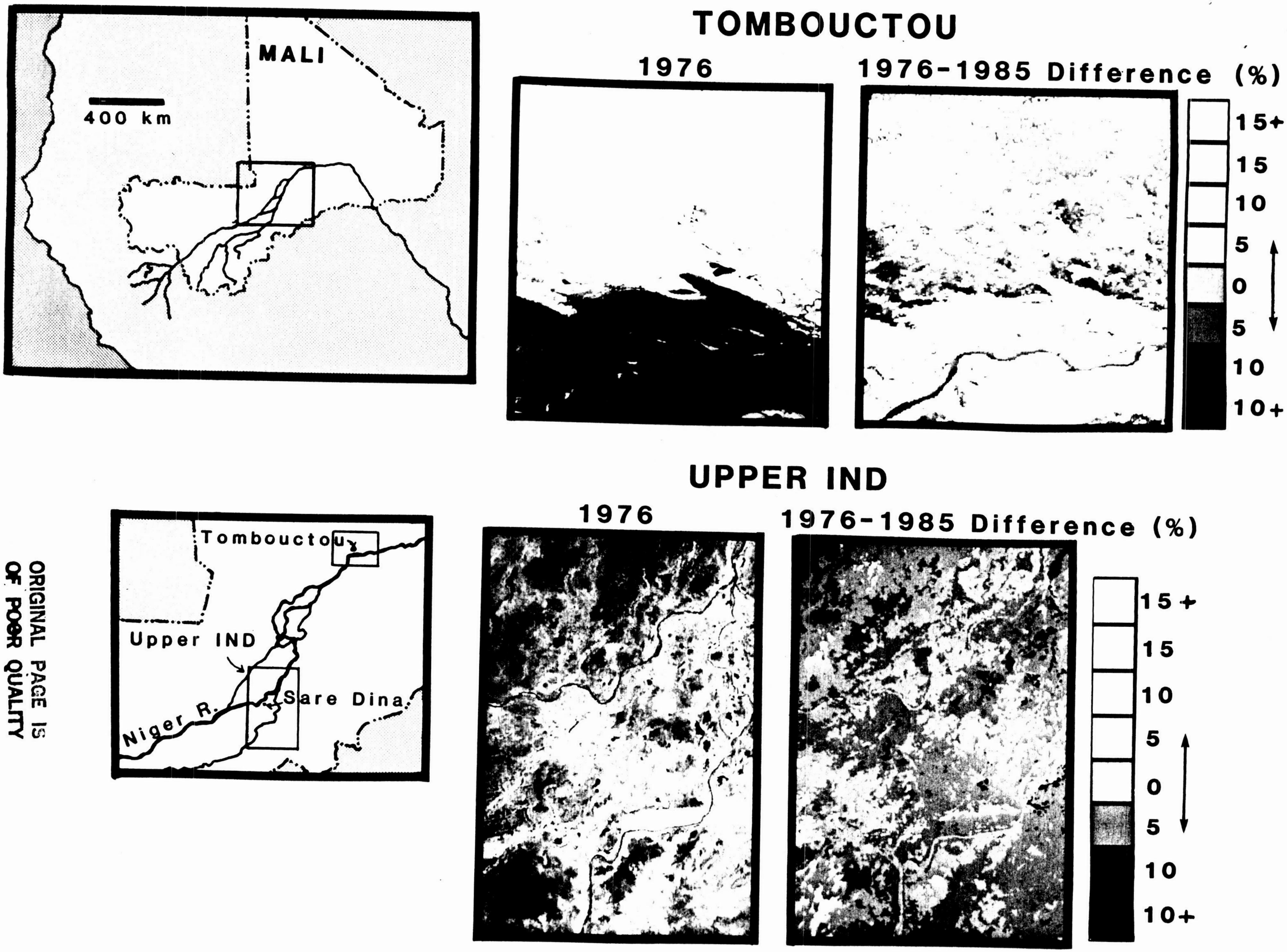
Analysis of MSS data acquired in 1976, 1984 and 1985, in conjunction with weather records for the period 1921-present, has yielded a preliminary baseline at MSS resolution for the magnitude and trend of surface brightness and color changes of the Azaouad dunes in the vicinity of Tombouctou. Working with calculated albedo images, image differences and field data, we have mapped drought-affected portions of the Azaouad as well as the Niger Bend floodplain south of Tombouctou. In the Azaouad dunes, changes in color and brightness at MSS resolution were found to be dominated by panchromatic brightness or "albedo," although field evidence indicates that brightness changes are related to both devegetation and surface remobilization of the dunes. (Trenches across selected dunes in 1985 field work revealed stable, semiconsolidated sand at depths of 40 - 100 cm.) It is anticipated that the better spectral resolution of the TM data will provide constraints on the subtle color characteristics of these changes. In the Niger Bend floodplain, differences between 1976 and 1985 data are dramatic enough that color information can be gleaned from MSS data. The 1985 data show abandonment of major distributary channels and desiccation of a significant portion of the floodplain, an area that was inundated through the dry season of 1976. Field inspection confirmed less than 5% vegetation cover, low soil moisture, and surface water confined to the main course of the Niger. Both MSS data and field observations revealed active dunes encroaching upon the north bank of the Niger east of Tombouctou.

These preliminary analyses also confirm significant changes to the environment immediately surrounding Tombouctou. In 1976, Tombouctou was surrounded by a well-demarcated bright halo approximately 5 km in diameter; 1985 data show that regional brightness has increased nearly to the level of the 1976 halo. This is characterized in the field by absence of vegetation, dune destabilization, and widespread gullying and other evidence of fluvial erosion. These changes are represented by the synthesized perspective diagrams of Figure 2.3.2, in which albedo as calculated from MSS data is plotted on the z-axis, with spatial contrast in MSS band 2 providing the surface texture. Thus, the leading edge of each diagram is an east-west albedo profile across the city. This figure shows the upward shift of baseline brightness.

The next phase of work for the Tombouctou region will be to incorporate TM data into the ten year sequence already established, to update trends observed in MSS data and to extract spectral information that will constrain the nature of changes to the region. The preliminary analyses with MSS data have allowed definition of a finite region for intensive study using TM. Over the course of the next 14 months, we will establish TM spectral baselines for dune crests, interdune areas and the Tombouctou vicinity, at three to four month acquisition intervals. The soil units that underly the dunes will be mapped using TM, and will be field checked to determine whether these units are physically distinct soil types or whether the observed differences relate to soil moisture, possibly yielding information on regional groundwater flow northward.

(References: Flohn, H. and Nicholson, S., 1980, Paleoecology of Africa 12:3-21; McIntosh, R., Geographical Journal 149:182-201.)

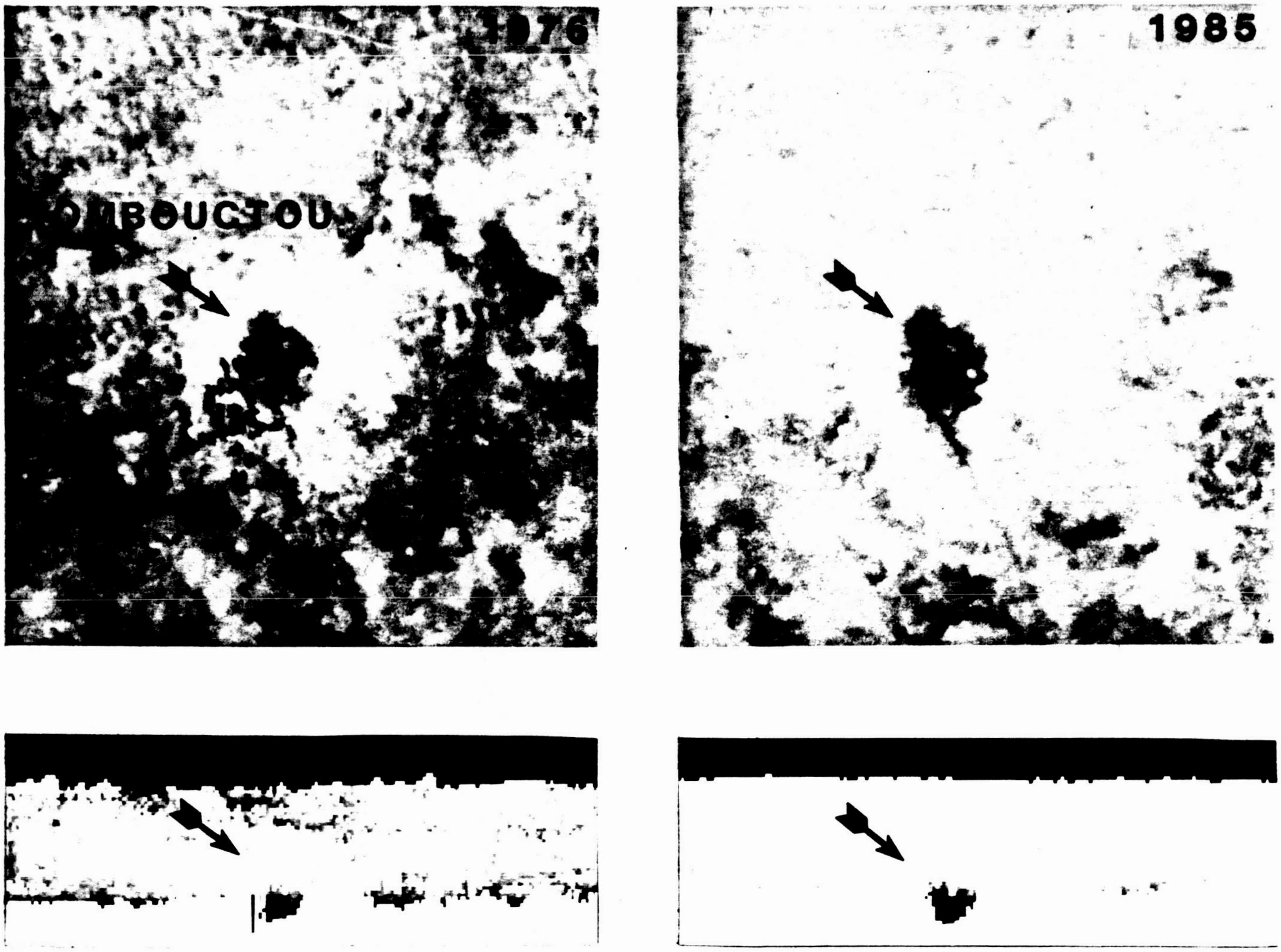
Figure 2.3.1: Sketch map showing the location of the Tombouctou/Azaouad study site within Mali. (The upper Inland Delta region, studied in a previous research program, is also shown). 1976 first principal components images are shown together with difference images calculated from both 1976 and 1985 MSS data, to establish basic trends within the data in preparation for TM analysis. (These images are discussed more fully in Attachment A.)



TOMBOUCTOU
1976
1976-1985 Difference (%)
15+
15
10
5
0
5
10
10+
MALI
400 km
UPPER IND
1976
1976-1985 Difference (%)
15+
15
10
5
0
5
10
10+
Tombouctou
Upper IND
Sare Dina
Niger R.

Fig. 2.3.1

Figure 2.3.2: Changes to the region surrounding Tombouctou are shown in this figure. Enhanced MSS images taken in 1976 and 1985 are presented, along with synthetic perspective diagrams designed to show the spatial character of brightness changes. It can be seen from these diagrams that regional brightness of the Azaouad dunes has increased relative to the city of Tombouctou over the past ten years.



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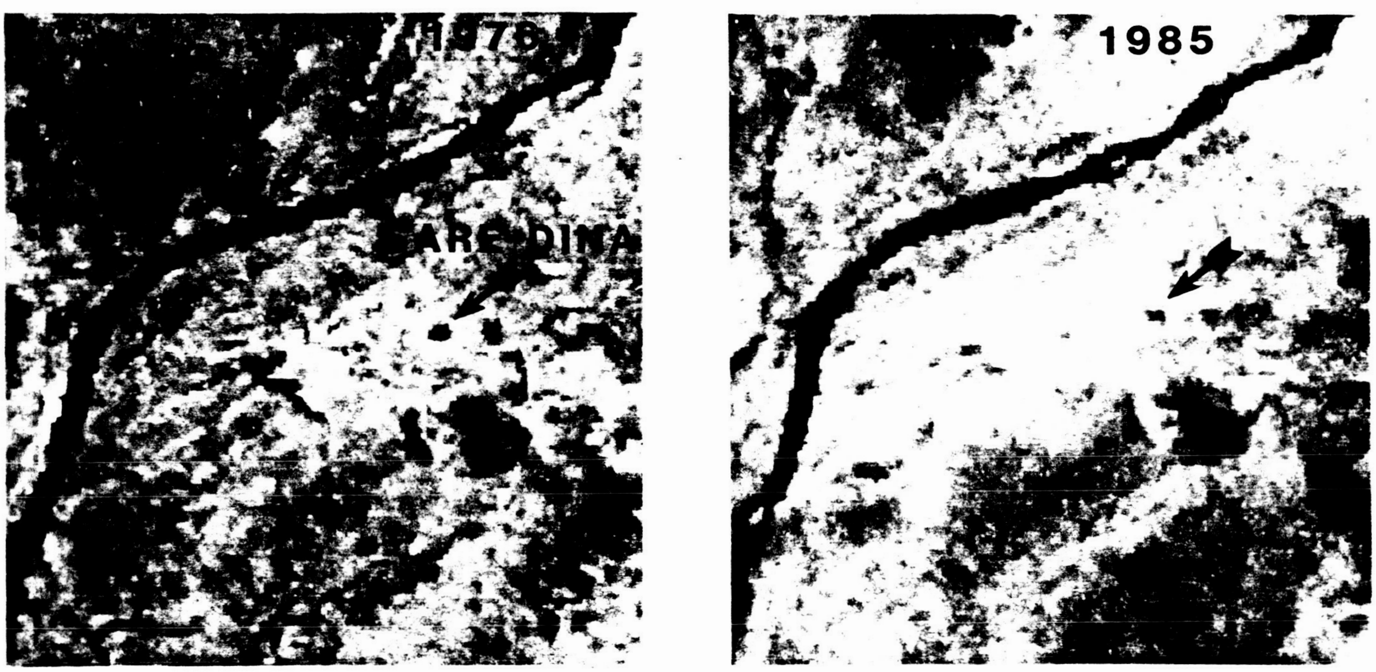

Fig. 2.3.2

3.1 Next Phase

Weather records for all field areas are being acquired on a monthly basis, and a program is being developed to "stack" these data into the multitemporal TM and MSS datasets. This will allow the identification of correlations between climatic variables and spectral trends identified in the orbital image data.

Over the next twelve months, it will be possible to begin relating baseline trends between field areas, as functions of climatic parameters. Field work is planned for Tombouctou in January 1987, with field work in the Okavango to occur in June 1987. During these field experiments, spectral measurements will be obtained using the HHRR acquired for this purpose. This will provide a means of correlating orbital spectra with ground-based data, and thus will provide not only ground truth but at least one tiepoint for atmospheric correction of the orbital data before long-interval baselines are established.

4.1 Attachments

The following is a listing of abstracts and papers produced over the past six months, for future publication.

Jacobberger, P.A., 1986, Remote sensing and field study of drought-related changes in the Inland Niger Delta of Mali, submitted to the Twentieth International Symposium on Remote Sensing of Environment: Remote Sensing for Africa, Nairobi, December 4-10, 1986.

Jacobberger, P.A., 1986, Mapping the abandoned fluvial system of the Azaouad Depression using MSS and TM data, submitted to the Twentieth International Symposium on Remote Sensing of Environment: Remote Sensing for Africa, Nairobi, December 4-10, 1986.

Maxwell, T.A. and Jacobberger, P.A., 1986, Remote sensing observations of sand movement in the Bahariya Depression, Western Egypt, submitted to the Twentieth International Symposium on Remote Sensing of Environment: Remote Sensing for Africa, Nairobi, December 4-10, 1986.

Jacobberger, P.A., 1986, Drought-related changes in the Inland Niger Delta of Mali, abstract submitted for presentation at the Geological Society of America Annual Meeting, San Antonio, November 10-13, 1986.

Hooper, D.M. and Jacobberger, P.A., 1986, Spectral characteristics of dunes and interdune corridors west of the Okavango Delta, Botswana, abstract submitted for presentation at the Geological Society of America Annual Meeting, San Antonio, November 10-13, 1986.

Jacobberger, P.A., Drought-related changes to geomorphologic processes in central Mali, submitted for review July 1986.

ATTACHMENT A

DROUGHT-RELATED CHANGES TO GEOMORPHOLOGIC PROCESSES IN CENTRAL MALI

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ABSTRACT

Geomorphologic evidence exists for repetitive drought conditions in the African Sahel; within this framework of broad climatic changes through time, the 1968-1985 drought episodes are not abnormal. However, the impact of recent drought on the economies and environments of Sahelian nations has been substantial, and the recovery capabilities of severely damaged lands are not well known. Study of the geomorphology and surface processes across a portion of Mali provides some constraints on the responses of desert fringe fluvial systems to changing environmental conditions. Multitemporal orbital image data were used in combination with field investigation to map drought-affected soils, and to document changes to both fluvial and aeolian processes across the region of study. A combination of statistical methods yields consistent evidence of net albedo increases associated with particular landforms and surface processes over a nine-year interval. Although aeolian processes are a significant transport mechanism for removal and redistribution of soil materials, both orbital data and field study indicate that fluvial erosion is responsible for much of the primary topsoil loss and landform modification in this portion of the Sahel.

INTRODUCTION

The Sahelian droughts of recent years are minor events when compared with the clear geologic evidence for past episodes of hyperaridity. The rainless years between 1968 and 1985 nevertheless have highlighted the problems and dramatic effects of drought (1). While the impact on the economies, agriculture and survival of Sahelian people has been immediate and visible, the longer-term consequences, distinct from famine and perhaps less well understood, are the changes in the dynamics of rivers and soils that result from years of rainfall deficiency. The processes that govern soil formation and erosion, river morphology and sediment transport capacity are necessarily linked to available moisture.

Stabilized dune cordons dated as much as 20,000 years before present reach from the southern margin of the Sahara to a limit far south of currently active dune systems, indicating past hyperarid episodes. The sedimentary remains of extensive water bodies in Saharan regions indicate that these dry episodes were separated by periods of more temperate climate (2). Thus, on a broad scale, Sahelian climate is highly variable. Weather records for this century also indicate several droughts ranging in length from a few years to nearly a decade, superimposed on a precipitation pattern of high interannual variability. The drought that began in 1968 and which has continued, with brief respites, into the mid-1980's, is therefore neither atypical nor unexpected.

Although precipitation levels for 1985 were encouraging for most of the Sahel, it would be premature to assume that the drought has ended; mild increases in rainfall also occurred in 1975, 1976 and 1978, yet severe drought returned in 1979 and persisted through 1984 (3).

The recovery capabilities of drought-damaged lands are not well understood. While a return to higher rainfall immediately will raise soil moisture and will promote ephemeral vegetation growth, the effects of some drought-related processes (destruction of perennial vegetation, topsoil erosion, and remobilization of stabilized dune sands) are cumulative, with long-term implications for real environmental recovery.

A combination remote sensing and field investigation, focussed on a portion of the Malian Sahel known as the Inland Niger Delta (IND), sheds some light on the relationships between Sahelian surface processes and drought (Figure 1). The name of this area results from the superficially "deltaic" appearance of the distributary channel system serving the Niger River between the cities of Jenne and Tombouctou. Annual floods during high rainfall periods prior to the drought have left thick deposits of silty soils throughout the region. Broad fields of ancient linear dunes which attest to past episodes of extended, Sahara-like hyperaridity are present across the area of study. During moist periods, these dunes were covered with vegetation which acted to stabilize the sand, preventing further dune movement. The total 400-kilometer long IND complex of channels, dunes and floodplains historically has been a locus of settlement, transportation and agriculture for the western Sahel.

Although the unique water resources of the Niger River have helped to buffer the region against widespread drought, the continued lack of rainfall has resulted in observable changes to the dominant morphologic processes of the area. Damage to soils and vegetation has been significant, and dramatic changes have occurred in river morphology and sediment transport capability. These changes have potentially long-term implications for post-drought recovery of the area.

METHODS

A number of studies of the Sahel have involved the use of remotely-sensed photographs and image data for broad regional morphologic mapping and land use inventory (4). By comparison, the current investigation represents a relatively detailed study of morphology and surface processes in a specific environmental setting, using both retrospective and current Landsat Multispectral Scanner (MSS) data at full spatial resolution (80 meters). These digital data were used to assess contemporary processes in the region, and to place these processes within the context of the drought.

The MSS data used in this study were obtained during the height of the dry seasons of 1976 and 1985. The 1976 data were used initially as a basis for mapping landforms and soils in representative locations in the IND. Following a five-week field study in January/February of 1985, 1976 and 1985 data were spatially co-registered for statistical analysis, image classification and albedo calculations.

Principal components analysis (PCA) is a means of minimizing correlations in order to optimize the availability of information embedded in the dataset (5). A great deal of correlation exists among the four spectral bands of a Landsat MSS data, due to the dominance of panchromatic brightness in controlling the brightness of individual bands. While such information is useful in mapping and visual interpretation of the image, subtle color differences can be obscured by this strong albedo effect. PCA essentially is a coordinate system rotation that provides a way of identifying correlated, panchromatic information and isolating it from minor (but potentially important) color trends. Typically, the statistically-transformed data are an ordered series of images, containing monotonically decreasing amounts of unique information (6). The first principal component will contain the highest amount of correlated information relating to panchromatic brightness; subsequent components will reveal subsidiary color trends relating to vegetation, soils and other sources of variance. If two MSS scenes are taken together in a principal components analysis, the resulting series of images will separate brightness trends common to both scenes from changes in brightness between scenes (7).

In this study, this technique was applied to merged 1976 and 1985 datasets. The first principal component images from these analyses contain most of the correlated information, and thus they define broad-scale, non-changing color patterns, while the second components identify regional brightness changes between 1976 and 1985. Table 1 lists the statistics pertaining to one of these eight-channel analyses. The sign reversal across the second component indicates significant increases in scene brightness between the two scene dates.

In order to determine the relationships between morphologic processes and the observed brightness changes, albedo images were calculated from the digital Landsat data, based on the methods described by Robinove (8). The albedo of a surface is a measure of its overall brightness, which in turn can be an indicator of vegetation cover, soil moisture, and in some cases, soil erosion (9). Because of the difficulty in determining accurately the atmospheric contribution to brightness within a satellite image, it is not feasible to calculate absolute albedos. However, the change in atmospheric contribution between two scenes can be assessed through examination of non-changing control areas in the images, and thus relative changes in albedo can be determined. Using this approach, the Landsat data were normalized for atmospheric and system differences.

In this study region, few non-changing areas exist, and the best control was obtained by using the spectral signatures for twenty villages scattered across the upper field area. The assumptions inherent in this approach are: 1) that village cores are non-changing areas; 2) that excess brightness due to atmospheric haze is uniform across the scene; and 3) that the change in village brightness due to atmospheric haze is additive (10). All villages used for control in the atmospheric corrections were observed in the field. Villages with significant vegetation were excluded, as were villages that covered less than four Landsat pixels. Calculations of albedo for the remaining villages indicated a mean brightness change of 10% $\pm$ 5%.

Following normalization, albedos were calculated as a linear combination of the four MSS bands in each scene, and the albedo differences (Δa) were obtained by subtraction:

$$\Delta a = \frac{\pi}{I \sin\alpha}\left[\left(\frac{DN_1}{G_1} + \frac{DN_2}{G_2} + \frac{DN_3}{G_3} + \frac{DN_4}{G_4}\right)_{1985} - \left(\frac{DN_1}{G_1} + \frac{DN_2}{G_2} + \frac{DN_3}{G_3} + \frac{DN_4}{G_4}\right)_{1976}\right]$$

where DN_n = digital value in channel n

I = solar radiance

G_n = gain value for channel n

α = solar elevation angle

These differences were plotted as thematic maps of albedo change, as shown in Figure 1.

RESULTS AND DISCUSSION

Areas showing greatest albedo increases are those in which water bodies (lakes, ponds, distributary channels) became desiccated over the study interval; these differences exceed 15% in areas where dry soil replaced surface water. Intermediate changes (10-15%) are associated with areas now having less than 15% vegetation and which commonly showed disruption of soil structure and loss of surface crust integrity. These characteristics are common to natural levees and floodplain silts along major distributaries of the Niger and Bani Rivers. Similar changes are visible in the western portion of the upper IND, which had moderate vegetation cover in 1976 but which had large tracts of bare soils and active dunes in 1985. Brightness increases in the Tombouctou area represent devegetation and surface remobilization of the linear dunes that cover the area; trenches across selected dunes reveal stable, semiconsolidated sand at approximately 40 cm depth. In 1976 image data, the Niger River floodplain south of Tombouctou was partially inundated and heavily vegetated throughout the dry season; 1985 data and field inspection of the region confirmed less than 5% vegetation, low soil moisture, and surface water confined to the main course of the Niger. Active dunes are now encroaching upon the north bank of the river.

Significant, land-use related changes also occur as well-defined high albedo halos around villages and towns. These halos are minimal in 1976, but are characteristic of the 1985 scene. In the field, very bright, disrupted soils, active aeolian transport of soil materials, and a near-total absence of vegetation defines these features. Gullying and other evidence of fluvial erosion is common. Around the town of Sare

Dina, shown in Figure 2, a circumscribed halo in 1976 is seen to have spread by roughly a factor of 10 over the decade study interval.

In 1976, Tombouctou also was surrounded by a distinct bright halo approximately five kilometers in diameter; by 1985, brightness of the outlying area had increased to the level of the 1976 halo, indicating significant vegetation loss and dune destabilization. This is represented graphically in the side-by-side "perspective" diagrams of Figure 2, in which albedo is plotted on the z-axis, and spatial contrast in MSS band 5 provides the surface texture. This approach results in an image in which bright areas are bright and high, and dark areas are both dark and low. The front edge of each perspective is an east-west albedo profile across the city. This figure shows the upward shift of the baseline brightness, as well as a signficant loss of contrast.

The atmospheric contribution to scene brightness discussed previously can be useful as a qualitative measure of atmospheric turbidity. Use of standard radiometric relationships show that the 10% change in atmospheric contribution is roughly equivalent to a factor of two increase in atmospheric turbidity (11). Assuming that the excess brightness is the result of an increase in airborne dust, this translate to a corresponding reduction in contrast transmissivity of 7.4 (12). One implication of this result is that extreme care should be exercised in interpreting orbital image data of areas showing high atmospheric contributions to scene brightness; reductions in apparent contrast will obscure both spectral and spatial detail. This effect is at least partially responsible for the contrast loss observed in Figure 2.

Although increased aeolian activity is a hallmark of drought processes, it is clear from both remote sensing analyses and field investigations that fluvial erosion has been invigorated by the drought regime. Extensive gullying, mentioned above in connection with the development of bright village halos, was also observed over much of the study region. Evidence of recent sapping was found on the Niger floodplain, and probably is related to documented lowering of the water table (13).

Fundamental changes have occurred within the anastomosing channel system of the Inland Niger Delta. Spectral properties of the Bani River show a brightening trend consistent with an observed increase in turbidity and decrease in water depth. A significant decrease in the number of dry-season active distributary channels is observed, both in the upper delta and near Tombouctou. Comparisons of measurements from the Landsat data show that the total water surface area in the upper delta in 1976 was 4% as compared with 1% in 1985. At the distal end of the delta near Tombouctou, surface water occupied 25% of the total image area in 1976, as compared with just 1% of the total in 1985. Apparent aggradation and abandonment of major distributary channels has occurred across the entire region.

Correspondingly, the data show a significant decrease in the sediment transport competence of the rivers. Point bars, beaches, and aggraded channels not visible in 1976 data were observed in 1985. One consequence of the reduced competence and corresponding enhanced depositional environment of the rivers is that large quantities of coarse grained fluvial sediment are made available for subsequent aeolian redistribution; this is corroborated by the common occurrence of mobile sand and active duneforms directly downwind of coarse-grained fluvial deposits.

The relationship between effective precipitation and sediment yield due to fluvial erosion has been discussed by Langbein and Schumm (14). Their model incorporates the stabilizing effect of vegetation cover, and predicts that sediment yield will be maximized at precipitation levels between 250 and 350 mm. Rainfall in the Inland Niger Delta during the drought years is consistent with maximum of sediment yield as predicted by this model (Figure 3), as well as in field and remote sensing observations.

CONCLUSIONS

Comparisons of 1976 and 1985 satellite data reveal a number of changes in the Inland Niger Delta, both in morphology and in the relationships among causative morphologic processes. Localized albedo increases in excess of fifteen percent are seen, against an average change of between 5 and 10%, plus or minus 5%. The largest albedo increases are associated with desiccation of surface water bodies; intermediate changes correlate with specific landform types, and are associated with changes in soil moisture, vegetation, and surface roughness characteristics. Marked albedo changes were observed in the vicinity of villages, and relate primarily to lack of vegetation, removal of topsoil and mechanical disaggregation of bright, exposed subsoils. These subsoils are largely impervious. Gullying is associated with increased runoff at the expense of infiltration, and disaggregation of soils facilitates aeolian transport of soil constituents. Lower discharges in rivers correlate with reduced transport capacity, which translates to increased fluvial deposition. In turn, large tracts of locally-derived fluvial materials are available for subsequent aeolian transport, and thus aeolian processes have been invigorated. The inability of distributary channels to handle the current sediment load has resulted in aggradation of many channels throughout the delta.

Continuation of these processes would result eventually in the abandonment of a significant portion of the Inland Niger Delta distributary system, with consequent evolution of a single-channel Niger morphology. Senescence of the distributary system would have profound implications for the economy and environment of the region. The delta channel complex acts as a catchment for water from the highlands in the upper portion of the Niger River basin, 800 km upstream, and the delay in flow peak that occurs in the delta appears to be a significant factor in the groundwater hydrology of central Mali (15). Annual flooding and the presence of the distributary channels form the basis for subsistence agriculture, pastoralism and transportation in central Mali, and are a major source of recharge for the shallow unconfined aquifers upon which most of the villages depend for water.

The post-drought recovery potential of the Inland Niger Delta and of the Sahel in general depends not only on the return of rainfall, but on the ability to the region to accomodate rainfall. Aggradation and abandonment of channels, loss of topsoil, and encroachment of mobile aeolian sands are drought-induced processes whose effects on the geomorphologic evolution of the region are far from understood, though the geologic record contains ample evidence for their previous occurrence.

Specifically, although aeolian processes clearly are important in Sahelian regions with regard to dune movement, fine sediment transport and atmospheric turbidity, understanding both the response of fluvial systems to drought and the connections between fluvial and aeolian processes is crucial to understanding the drought environment and its consequences (16).

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10. It should be noted that at values of ground reflectance in the range 0.2-0.5, the effects of skylight on space reflectance are minimized; at surface reflectances above 50%, the assumption of linearity will result in an overestimation of the importance of atmospheric haze to scene brightness, with a corresponding unnderestimation of albedo change (K. Ya. Kondratyev, L. N. Dyachenko, N. P. Piatovskaya, in Earth Survey Problems (Berlin, Akademie-Verlag, 1974) pp. 473-482; J. Otterman, R. S. Fraser, Remote Sensing of Environment 5, 247-266 (1976); J. Otterman, S. Ungar, Y. Kaufman, M. Podolak, Remote Sensing of Environment 9, 115-129 (1980); A. J. Richardson, Applied Optics 21, 1457-1464 (1982).

11. The relationship between reflectance and atmospheric turbidity is defined as follows:

$$I = \left(I_0/_S\right) \exp\ (-\tau\ m)$$

so that $$\Delta\left(I/I_0\right) = \left[\frac{1}{S} \exp\ (-\ \tau\ m\ )\right]^{1985} - \left[\frac{1}{S} \exp\ (-\ \tau\ m\ )\right]^{1976}$$

and $$\frac{\tau^{1985}}{\tau^{1976}} = \ln\left(\Delta\ I/I_0\right)$$

where I = direct flux τ = turbidity

I_0 = solar flux m = mean path length

S = solar distance factor

12. T1 contrast transmissivity can be defined as the observed contrast betwen two pixels with an inherent contrast C, where a = pixel of higher reflectance and a = pixel of lower reflectance:

$$T_1 = \frac{1}{C}\frac{a_s(a_h)}{a_s(a_l)} - \frac{1}{C}$$

$$= \frac{a_h - a_l}{C\ a_l}$$

$$\text{and } \Delta T = \left[\frac{a_h - a_l}{C\ a_l}\right]^{1985} - \left[\frac{a_h - a_l}{C\ a_l}\right]^{1976}$$

The same results are calculated for T2 transmittance (across a straight line boundary) and T3 transmittance (between a large, bright area and a single dark pixel). (J. Otterman, S. Ungar, Y. Kaufman, M. Podolak, Remote Sensing of Environment 9, 115-129 (1980).

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TABLE 1

	1976				1985			
	CH1	CH2	CH3	CH4	CH1	CH2	CH3	CH4
MEANS	23.61	33.59	39.62	33.34	46.55	66.54	71.86	64.99
S.D.	8.92	13.92	15.34	12.70	9.84	14.52	15.99	14.48
C.VAR.	0.38	0.41	0.39	0.38	0.21	0.22	0.22	0.22

EIGENVECTOR MATRIX

									%VARIANCE
PC1	0.024	0.025	0.026	0.025	0.026	0.027	0.028	0.027	76.03
PC2	0.027	0.030	0.030	0.029	−0.023	−0.023	−0.023	−0.024	20.33
PC3	0.053	0.040	−0.019	−0.045	0.007	0.009	0.000	−0.013	1.34
PC4	0.044	−0.027	−0.005	0.019	0.064	0.016	−0.017	−0.024	1.06
PC5	−0.073	0.016	0.022	−0.019	0.028	0.024	−0.006	−0.028	0.58
PC6	−0.032	0.030	−0.043	0.043	0.005	0.005	−0.003	−0.004	0.38
PC7	−0.016	0.014	0.002	−0.012	0.058	−0.034	−0.021	0.034	0.20
PC8	0.003	0.000	0.001	−0.002	−0.029	0.037	−0.043	0.028	0.08

FIGURE CAPTIONS

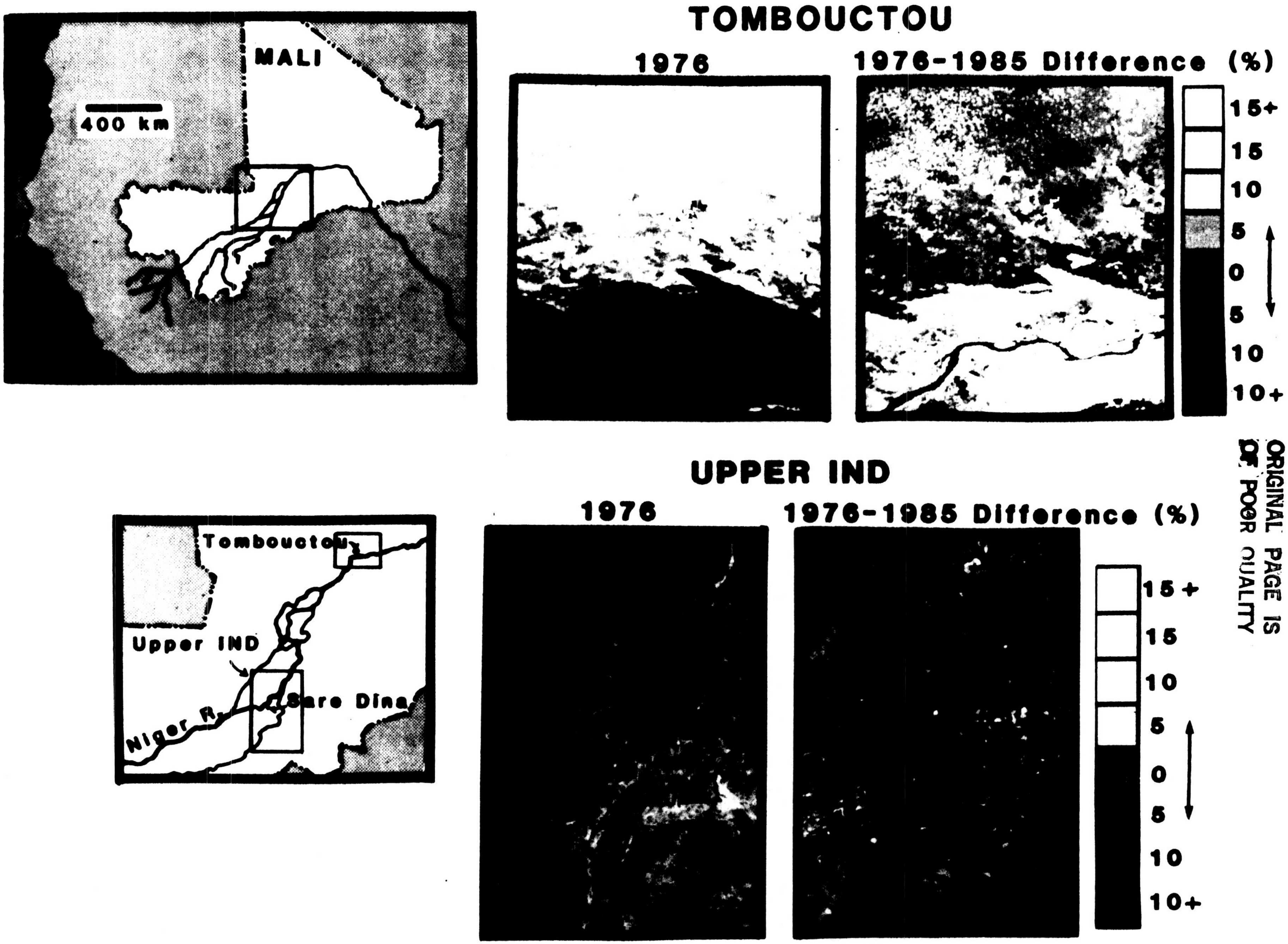
Figure 1: The Inland Niger Delta (IND) of Mali lies within the Sahel, and although the water resources of the Niger River have helped to ameliorate drought conditions, persistent lack of rainfall has caused significant changes in the region. Albedo calculations based on the digital brightness values obtained from Landsat MSS data reveal broad increases in albedo or surface brightness. These changes, shown for two subsets of the study region, correlate particular landforms (notably levee deposits and dune sands). Enhanced, first principal component images are shown for landform comparison.

Figure 2: Over the course of the 1976-1985 study interval, the well-defined bright halos that characteristically surround villages in the Sahel were observed to expand and coalesce. Shown here are 1976 and 1985 albedo images for Sare Dina (A) and Tombouctou (B). Field inspection of these and other village halos show them to be areas barren of vegetation and characterized by powdery, dry soils and marked fluvial erosion. In 1976, these halos are circumscribed; in the 1985 images, the halos have spread to cover a much larger area around the village and in adjacent lands. Synthetic albedo "relief maps" shown for Tombouctou illustrate the spatial nature of this expansion. The leading edge of each of these diagrams essentially

represents an albedo profile across Tombouctou, and the remainder shows albedo variation north of the city. The canals and ponds west of Tombouctou have become dry, and the brightness of the surrounding region has increased. Coupled with these changes is an overall loss of contrast in the 1985 data; this is partly due to real increases in surface brightness, and partly due to reduced contrast transmissivity as a result of atmospheric dust.

Figure 3: The relationship between sediment yield and precipitation as proposed by Langbein and Schumm is shown graphically, plotted together with IND precipitation levels through time. The drop in precipitation expressed in five-year increments correlates with maximum predicted sediment yield, which in turn is consistent with field observation. The years of drought have fostered an invigoration of both fluvial erosion (hence high sediment yield) and aeolian transport of fluvially-derived materials.

TABLE 1: Statistics pertaining to a principal components transformation applied to two "stacked" four-channel Landsat MSS images show the distribution of variance across the dataset. Channel means, standard deviations and coefficients of variance are shown in the upper portion of the table. The corresponding eigenvector matrix, with each vector presented as a row of individual channel contributions, shows the equal contributions of all channels to PC1, and the high percent variance contained in the PC1 vector. PC2 explains over 20% of the variance inherent in the dataset; the sign reversal across PC2 indicates control of this vector by broad differences between 1976 and 1985 channels of data.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1976-1985 Difference (%)
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1976
1976-1985 Difference (%)
15+
15
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0
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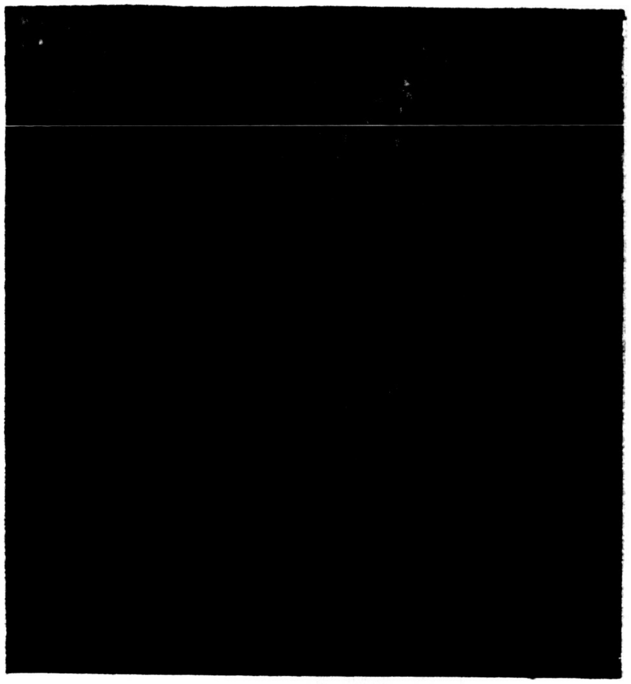
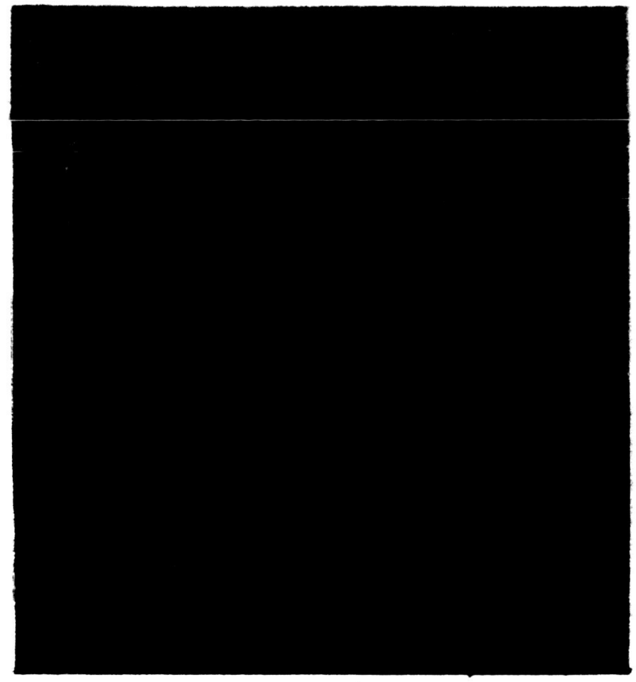
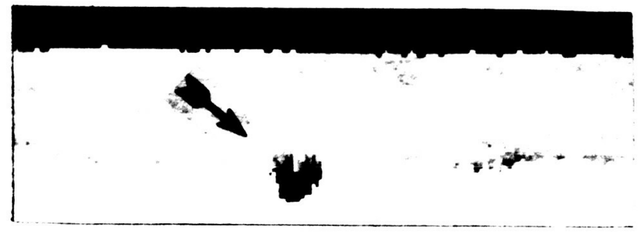
10
10+



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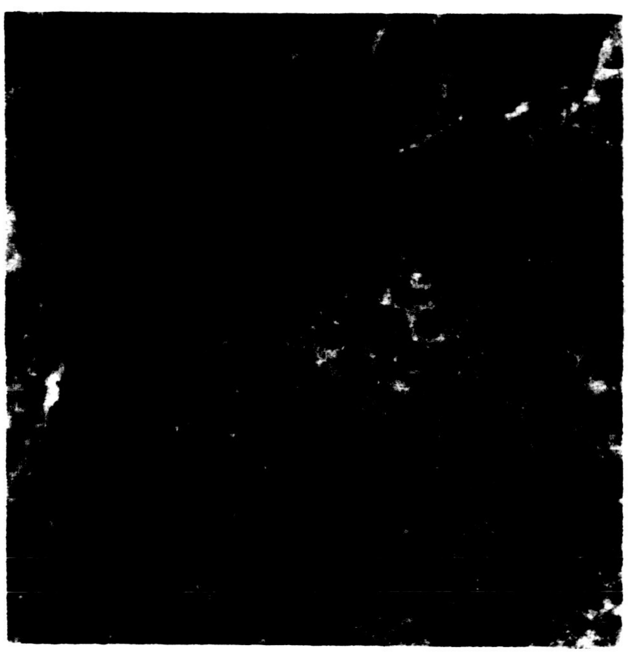
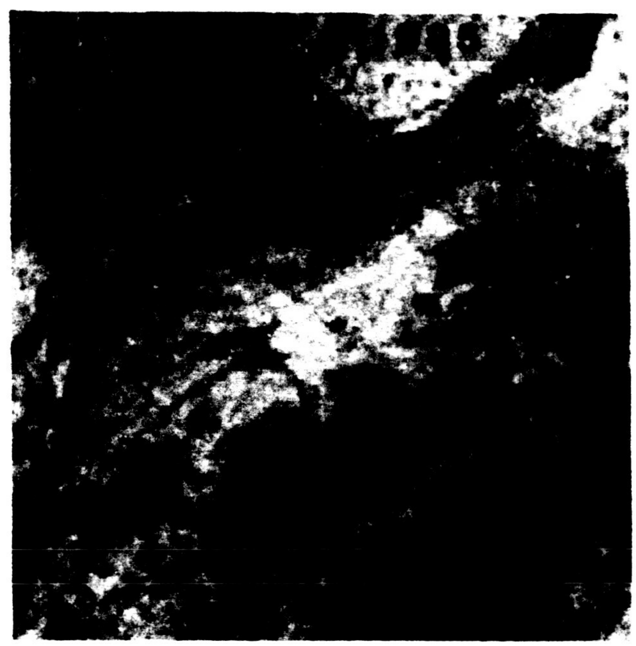

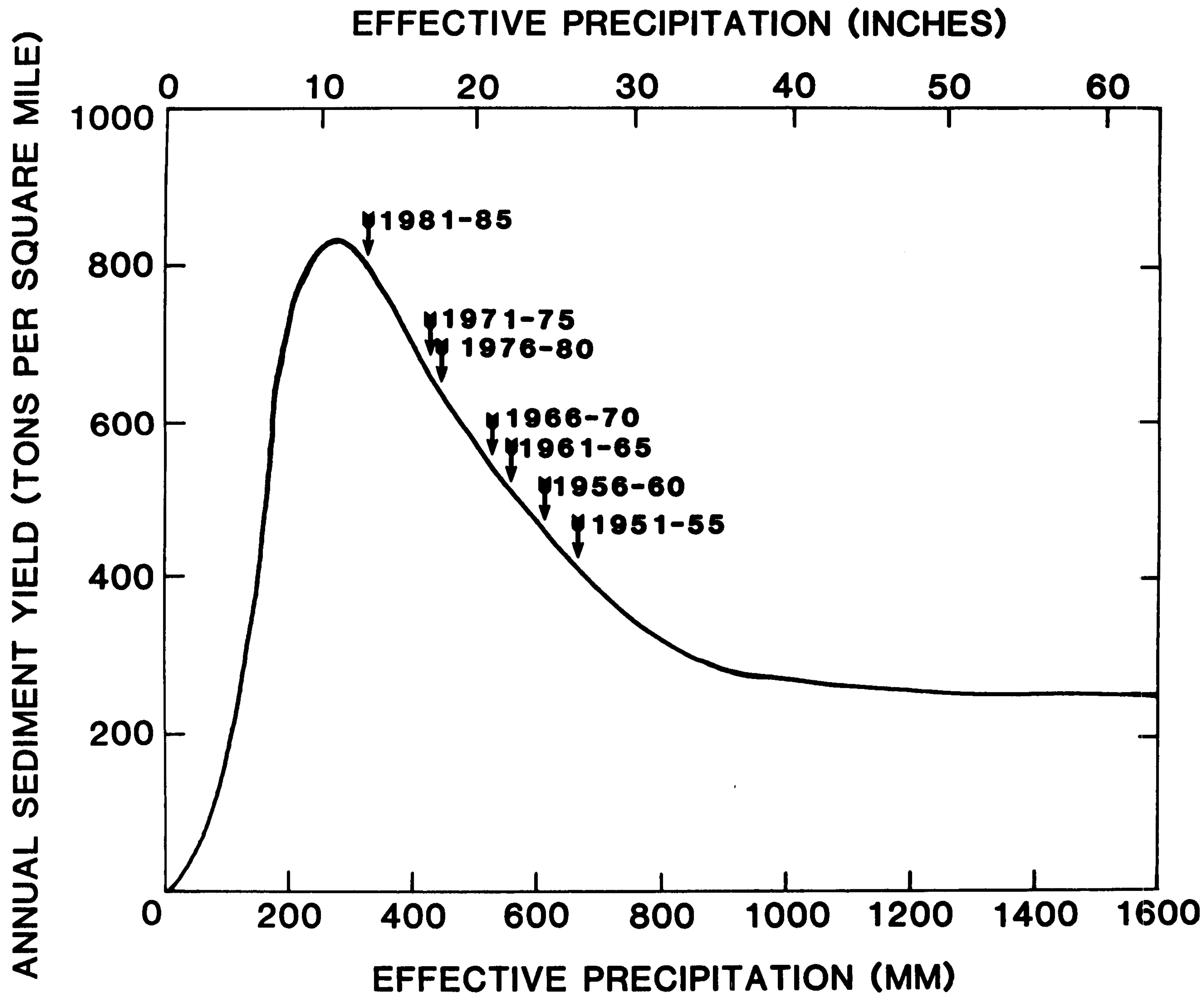
EFFECTIVE PRECIPITATION (INCHES)
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ANNUAL SEDIMENT YIELD (TONS PER SQUARE MILE)
200
400
600
800
1000
1200
1400
1600
EFFECTIVE PRECIPITATION (MM)

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DROUGHT-RELATED CHANGES IN THE INLAND NIGER DELTA OF MALI

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Like most of the Sahel, central Mali has been subject to drought conditions since 1968. The results of a multitemporal remote sensing and field study of the Inland Niger Delta (IND) of Mali provides some constraints on the responses of desert fringe aeolian and fluvial systems to changing environmental conditions.

Multitemporal orbital image data (1976-1985) were used in combination with field investigation to map drought-affected soils, and to document changes across the region. Statistical analyses indicate albedo increases associated with particular landforms and surface processes. Albedo changes in excess of 15% correlate with desiccation of surface water bodies and abandonment of distributaries and floodplain. Lesser increases correlate with vegetation loss, disruption of soil structure and loss of surface crust integrity. Near Tombouctou, changes represent vegetation loss, surface remobilization of dune sands, and a substantial decrease in vegetation and surface water in the Niger floodplain. Abandonment of major channels in the IND distributary system was observed in all areas studied. High albedo halos, characterized by very bright, disrupted soils, widespread aeolian transport of soil materials, and a near-total absence of vegetation, are visible around villages. Gullying and other aspects of fluvial erosion are common.

Although aeolian processes are a significant transport mechanism ffor removal and redistribution of soil materials, both orbital data and field study indicate that fluvial erosion is responsible for much of the primary topsoil loss and landform modification in this portion of the Sahel.

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- ☐ 2 coal geology
- ☐ 3 economic geology
- ☐ 4 engineering geology
- ☐ 5 environmental geology
- ☐ 6 general geology
- ☐ 7 geochemistry
- ☐ 8 geology education
- ☑ 9 geomorphology
- ☐ 10 geophysics
- ☐ 11 geoscience information
- ☐ 12 glacial geology
- ☐ 13 history of geology
- ☐ 14 hydrogeology
- ☐ 15 marine geology
- ☐ 16 mathematical geology
- ☐ 17 micropaleontology
- ☐ 18 mineralogy/crystallography
- ☐ 19 oceanography
- ☐ 20 paleontology/paleobotany
- ☐ 21 petroleum geology
- ☐ 22 petrology, experimental
- ☐ 23 petrology, igneous
- ☐ 24 petrology, metamorphic
- ☐ 25 petrology, sedimentary
- ☐ 26 planetary geology
- ☐ 27 Precambrian geology
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№ 93386

SPECTRAL CHARACTERISTICS OF DUNES AND INTERDUNE CORRIDORS WEST OF THE OKAVANGO DELTA, BOTSWANA

HOOPER, Donald M. and JACOBBERGER, Patricia A., Center for Earth and Planetary Studies, National Air and Space Museum, Washington, D.C. 20560

Digital Landsat Thematic Mapper (TM) data are being used to map dune morphology and spectral characteristics of stabilized dune sands in the Kalahari Desert of northwestern Botswana. This dune system is composed of vegetation-covered linear dunes which average two kilometers across and tens of kilometers in length, and is bordered on the east by the Okavango Swamp. The Okavango Swamp is hydrologically complex, and in normal years serves as a catchment, distributary system and groundwater recharge area for the Okavango River. Mappable differences exist in dune and interdune corridor morphology, and spectral variations occur across the dune system. In recent years, the Kalahari has been subject to severe drought stress, resulting in changes in vegetation cover and soil moisture as seen through examination of Landsat Multispectral Scanner images, TM data and Hasselblad photos acquired during Shuttle missions.

Although both dunes and interdune corridors west of the swamp are vegetated and dune crests are subdued, the interdune corridors are well-defined, narrow, linear and marked by very high-reflectance margins. In comparison, the related dunes north of the swamp have been bevelled and breached by ephemeral distributaries of the Okavango system. These differences indicate that although surface runoff modifies the dunes north of the swamp, infiltration is the primary source for the western dunes. Spectral variations and dune characteristics are being used as a basis for a broad multitemporal comparison of vegetation abundance and soil condition over the last fifteen years, to detect changes due to drought stress. The photometric information that will result from these analyses also will be used subsequently for the development of a remote sensing-based model characterizing the morphometry of stabilized dunes.

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REMOTE SENSING AND FIELD STUDY OF DROUGHT-RELATED CHANGES IN THE INLAND NIGER DELTA OF MALI

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Washington, D.C. 20560 USA

Like most of the Sahel, central Mali has been subject to drought conditions since 1968. Examination of rainfall records for stations within the upper Inland Niger Delta (IND) of Mali show that rainfall between 1971 and 1984 was 20% below the longterm average, and rainfall from 1982 through 1984 was reduced by 40%. The response of fluvial and aeolian processes to such dynamic changes is not well known. The results of a multitemporal remote sensing and field study of a portion of the IND provides some constraints on the responses of desert fringe fluvial systems to changing environmental conditions.

Multitemporal orbital image data were used in combination with field investigation to map drought-affected soils, and to document changes to both fluvial and aeolian processes across the region of study. Analysis of 1976, 1984 and 1985 digital Landsat MSS data for the upper IND indicate that the reduction in available surface moisture has had a significant effect on the soils and dominant surface processes of the region, including a >75% decrease in the total surface area of lakes, ponds and swamps mapped as permanent water bodies in the 1950's. Image data for 1985 show formerly permanent distributary river channel as dry stream beds. The Niger and Bani Rivers are seen to be underfit and less competent to transport sediment than in 1976. Landsat data also show widespread reactivation of previously stabilized linear dunes, as well as encroachment of small, active linear dunes and sand stringers over areas downwind from modern river beaches and bars.

A combination of statistical methods yields consistent evidence of net albedo increases associated with particular landforms and surface processes over the nine-year study interval. Albedo changes in excess of 15% correlate with desiccation of surface water bodies and abandonment of distributaries and floodplain. Upon field examination, areas with intermediate changes (10-15%) were found to lack vegetation and commonly showed disruption of soil structure and loss of surface crust integrity. Spectral signatures in the 1976 data indicated moderate vegetation cover at that time. Near Tombouctou, changes in color and albedo were found to represent devegetation and surface remobilization of the linear dunes that cover the area, and a substantial decrease in vegetation and surface water in the Niger floodplain to the south. Abandonment of major channels in the IND distributary system, with related albedo increases due to loss of vegetation, soil moisture and soil integrity, were observed in all areas studied.

Land-use related albedo increases also are visible as broad, well-defined halos around villages and towns. In the field, halos are characterized by very bright, disrupted soils, widespread aeolian transport of soil materials, and a near-total absence of vegetation. Gullying and other evidence of fluvial erosion is common in the upper delta.

Although aeolian processes are a significant transport mechanism for removal and redistribution of soil materials, both orbital data and field study indicate that fluvial erosion is responsible for much of the primary topsoil loss and landform modification in this portion of the Sahel.

MAPPING THE ABANDONED FLUVIAL SYSTEM OF THE AZAOUAD DEPRESSION USING MSS AND TM DATA

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Smithsonian Institution
Washington, D.C. 20560 USA

The Inland Niger Delta occupies an area covering roughly 120,000 square kilometers of the central Malian Sahel. The upper portion of the delta is composed of a network of distributary channels which flow northward, converge at Lake Debo, and split again into several highly sinuous channels that wind through the Late Pleistocene Erg of Bara dune complex. These channels converge again, and the Niger resumes a single low-sinuousity channel morphology near Tombouctou. The Azaouad Depression occupies the region north of Tombouctou, and is characterized by another distinctive complex of old, stabilized linear sand dunes (the Erg of Azaouad). These dunes trend roughly N 67°E with nominal wavelengths of 1500 meters. The construction of the Azaouad dunes has been dated to a hyperarid episode between 20,000 and 12,000 years before present. Stabilization is thought to have occurred during a humid phase between 12,000 and 8,000 years bp. Holocene remobilization of the southern Erg of Azaouad sands between 8,000 and 7,000 ybp, followed again by stabilization between 6,000 and 5,000 ybp, has been suggested based on geomorphologic relationships and the climatic chronologies established for other Sahelian regions.

Intercalated with the dunes of the Azaouad system are relict fluvial channels leading north into the Azaouad Depression. These channels represent either former courses or major distributaries of the Niger River; prior northward drainage of the Niger into the now-hyperarid Sahara has been suggested.

Although most of the relict fluvial system and associated soil units in the Azaouad are indistinguishable in visual observations, Skylab photographs and Shuttle Hasselblad images of the region, spatial filtering of digital Landsat MSS and TM data allowed removal of the 1500-meter wavelength dune pattern. Residual images show an extensive network of the Azaouad paleochannels. Although only the larger channels (first-and second-order) are resolvable in filtered MSS data, the higher resolution of TM data permits identification of some third-order channels and channels apparently antecedent to the primary drainage network. The Azaouad paleodrainage is poorly organized, with no apparent control of the first or second-order channels by the dunes. No first-order channels are seen to parallel the dunes or to occupy interdune corridors, although there are indications of smaller, higher-order distributaries in the interdune areas.

The observed morphology indicates that these channels postdate the formation of the Erg of Azaouad dunes. Fluvial modelling and breaching of the dunes point to water volumes sufficient to overcome the low regional gradient and physical barrier of the sand. No channels are observed in the region showing most evidence of Holocene dune remobilization and reworking, indicating that the channel system may predate this episode (8,000 - 7,000 ybp). The morphometry of the channel complex is similar to that of the present Inland Niger Delta in the region of the Erg of Bara, suggesting a possible northward extension of the Inland Delta of the Niger across the southern Azaouad between 10,000 and 8,000 ybp.

REMOTE SENSING OBSERVATIONS OF SAND MOVEMENT IN THE BAHARIYA DEPRESSION, WESTERN EGYPT

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Patricia A. Jacobberger
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National Air and Space Museum
Smithsonian Institution
Washington, D.C. 20560

Although multispectral satellite images have been available only for the past 14 years, the time scale for observations of environmental changes can be extended by using aerial photography taken several decades ago. For studies of sand transport in arid regions, this extended interval is extremely valuable in that large dunes move much slower than can be detected with the 14 year record of Landsat MSS data. Field studies in southern Egypt indicate that fast-moving barchan dunes move at an average rate of 7-10 m/yr, which equates to only a one to two pixel change over the entire record of Landsat data. In the Bahariya depression in western Egypt, we are extending our dune migration studies to multitemporal MSS and Thematic Mapper by using aerial photographs taken over 30 years ago. Used together, these complementary data sets indicate natural environmental changes due to dune migration, as well as the impact of human habitation in an active sand transport regime. In addition, the spectral information contained in Thematic Mapper data is being used to map compositional variations in dune and desert floor sediments.

The central part of the Bahariya depression is covered by irregular sand masses 3-5 km wide. The distribution of these sand masses is controlled primarily by the relict fluvial topography of the north escarpment of the depression. Isolated plateaus and hills within the depression create local variations in the predominant northerly winds, and exert additional control on the patterns of aeolian erosion and deposition. The boundaries of these sand masses as mapped on air photos and Landsat images have changed little over a 30-year period, although local movement of linear dunes has occurred. The most evident changes are due to cultural influences. Approximately 40% of the area occupied by active sand deposits in the early 1950's is seen to be cultivated land in 1985. Areas of the sand masses that formerly had a high density of individual vegetated mounds are now joined by belts of cultivated fields, which can be resolved in the 1985 Thematic Mapper data.

Field investigations of this region during 1985 support the environmental changes seen in the remote sensing data. Inhabitants of Bahariya are increasingly cultivating the dune sand that occupies the lowest parts of the depression, rather than losing fertile land due to dune encroachment. Although such areas have the highest risk of sand infiltration into the cultivated fields, the availability of near surface ground water makes this activity a natural consequence of coexistence with active aeolian sand. SPOT images of this region will be acquired in the summer of 1986, and will be used to compare short term variations in dune form due to seasonal wind direction changes with the long term trends already established.